

5th International Workshop On

# Critical Point and Onset of Deconfinement (CPOD)

June 8-12, 2009 at Brookhaven National Laboratory

# Hadron production in Al + Al collisions at 2A GeV

Piotr Gasik

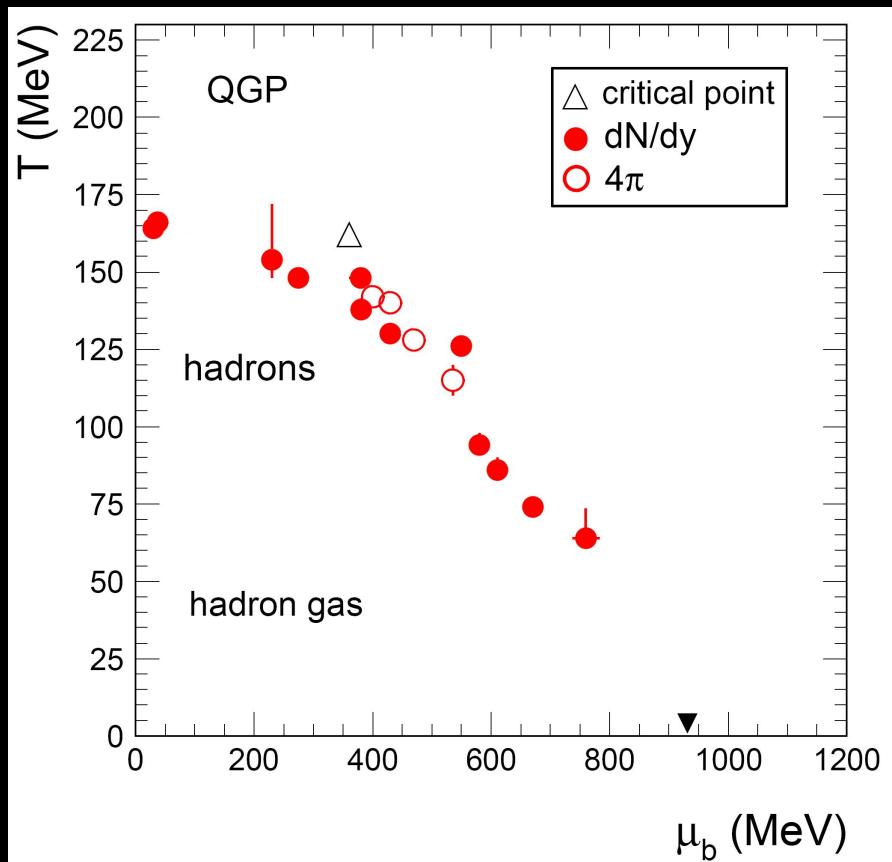
for the FOPI Collaboration

*University of Warsaw, Poland*



# Motivation

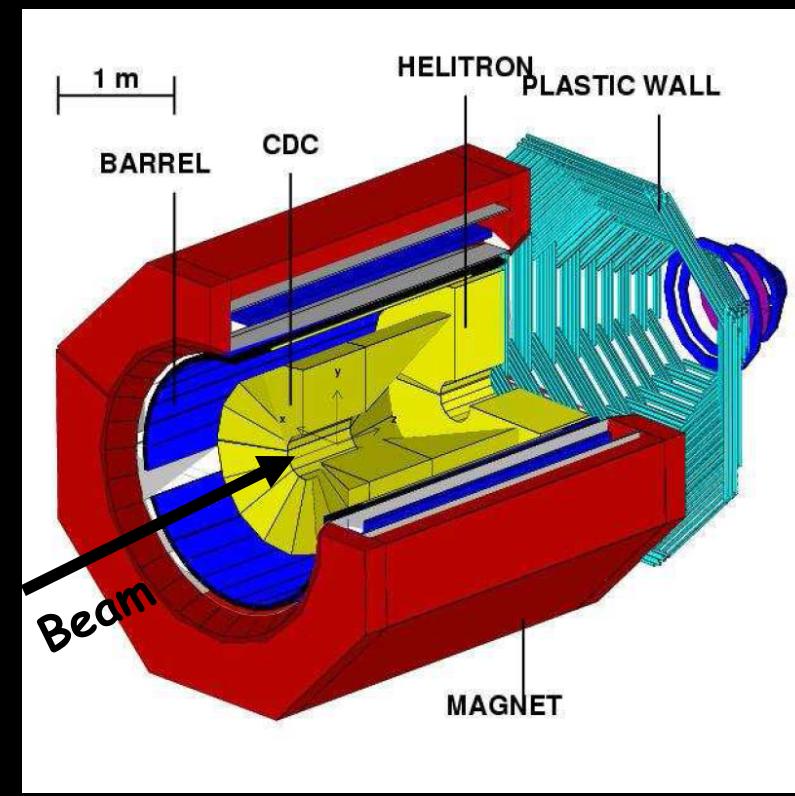
- Nuclear collisions at SIS energies (up to 2A GeV)
- Measuring as many yields of produced particles as possible (FOPI detector)
- In which region of phase diagram are we?
- Is there an equilibrium at such energies?



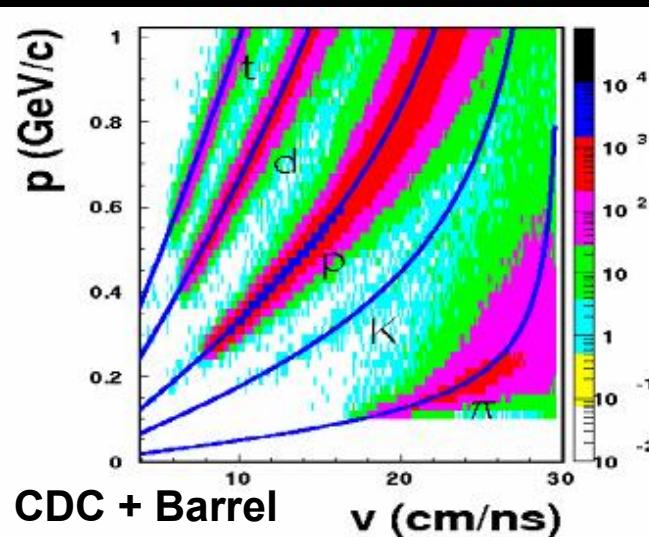
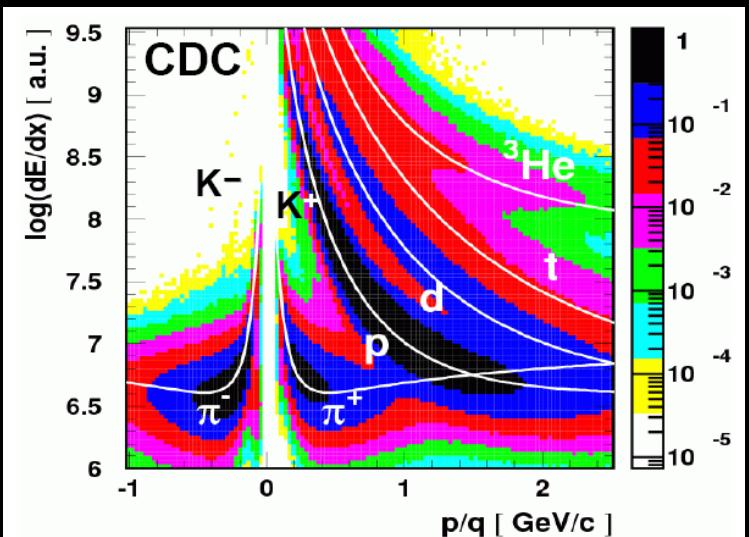
A. Andronic,  
P. Braun-Munzinger,  
J. Stachel,  
NPA 772 (2006) 167

# FOPI Detector @ GSI

- Almost full  $4\pi$  coverage
- 2 types of detectors:
  - gas chambers ( $dE/dx$ ,  $p_t$ )
  - scintillators (ToF)
- Magnetic field  $B=0.6$  T
- Measured particles:  
 $p, d, t, {}^3\text{He}, \pi^\pm, K^\pm$  – direct identification  
 $\Lambda, K^0, K^*, \Sigma^{\pm*}, \phi$  – invariant mass reconstruction



Particles identification in FOPI:

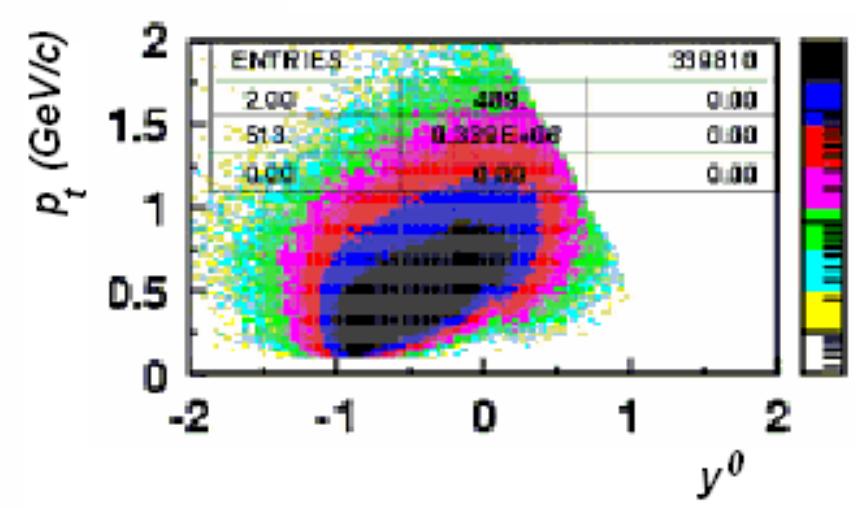


Al+Al @ 1.91A GeV experiment (2005)

- $400 \cdot 10^6$  most central (20%) events collected
- 10 TB raw data

# Proton yield

Phase space distribution  
of measured protons



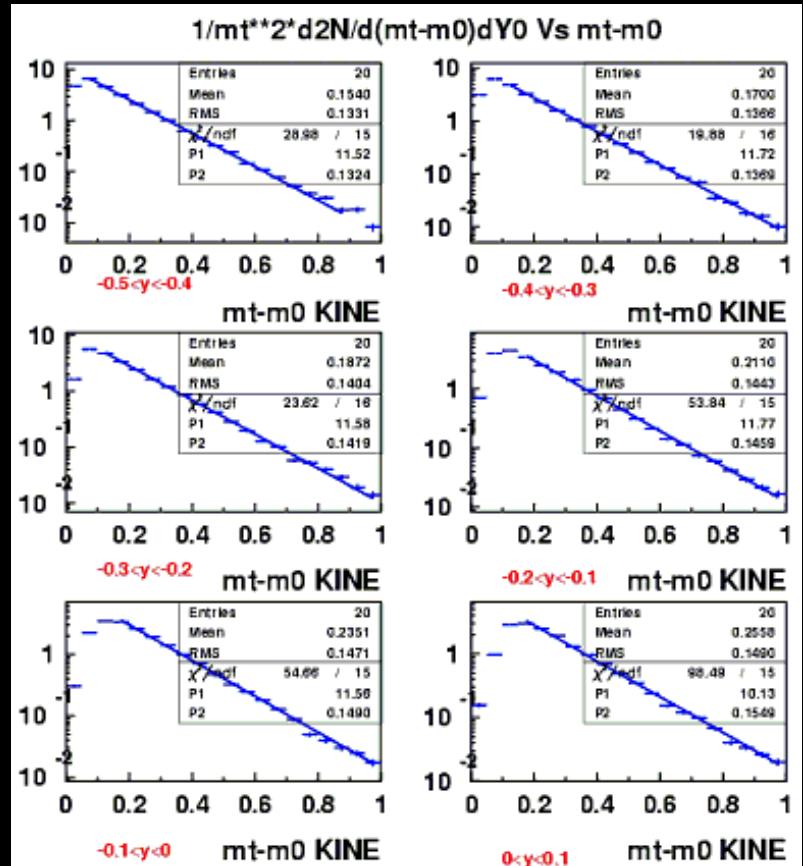
$$y^0 = \frac{y}{y_{cm}} - 1$$

$y^0 = -1$  ... target rapidity

$y^0 = 0$  ... midrapidity

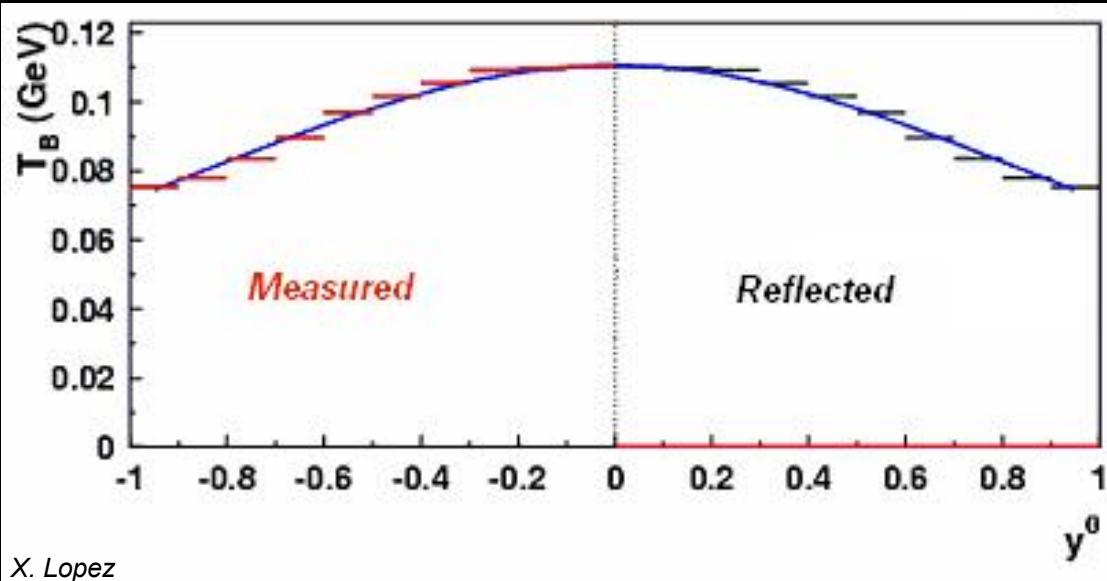
$y^0 = +1$  ... projectile rapidity

$M_t$  spectra for different  
rapidity ranges

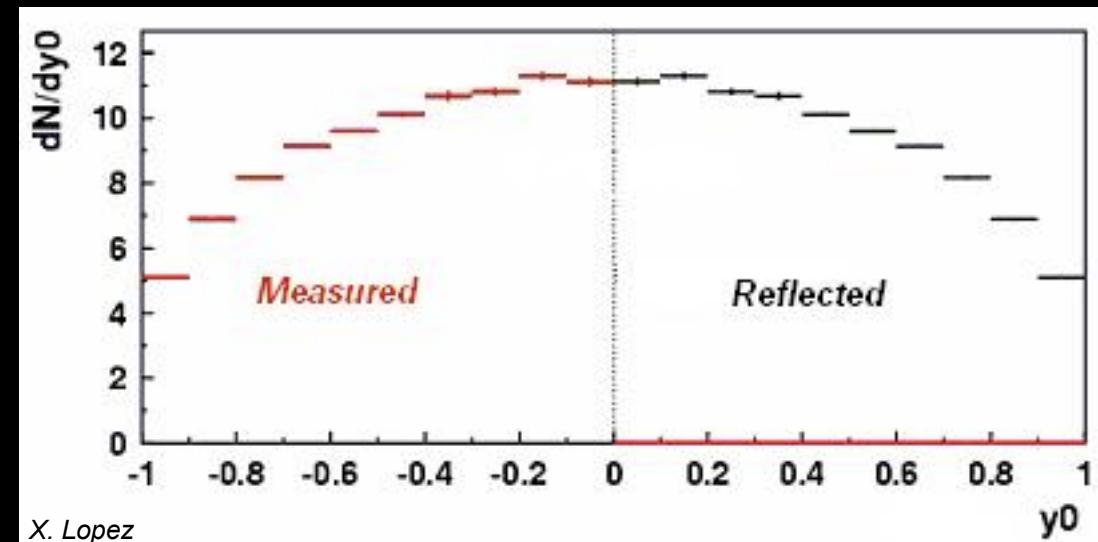


X. Lopez for the FOPI Collaboration

# Proton yield



Temperature at midrapidity:  
 $T_{\text{kin}} = (110 \pm 6) \text{ MeV}$



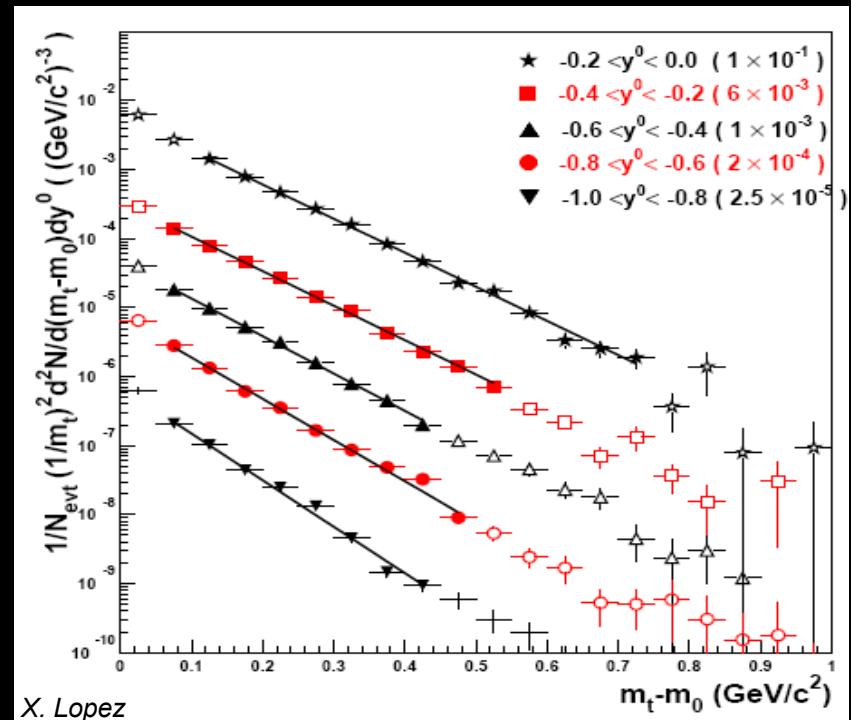
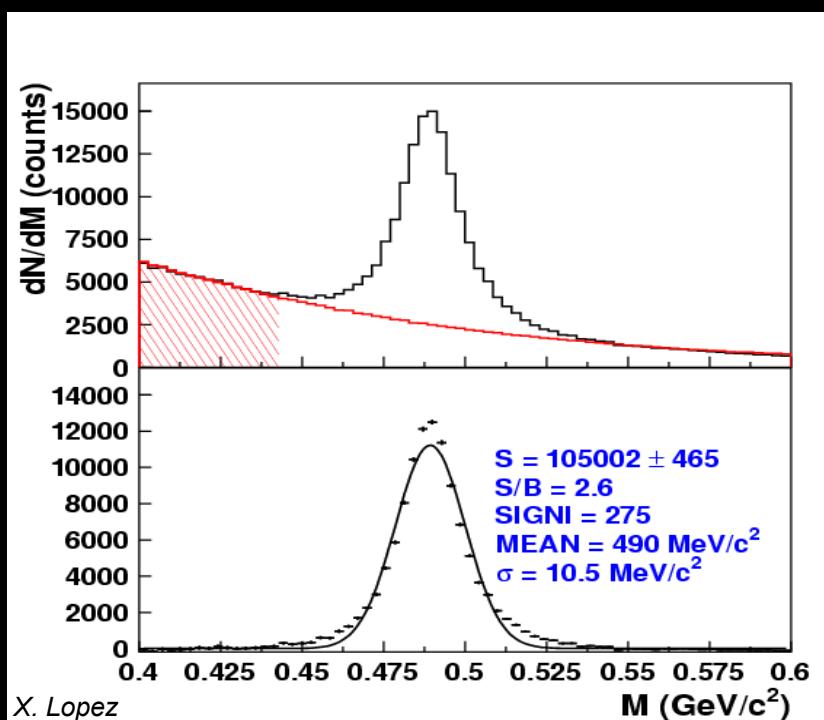
Total proton yield:  
 $\approx 19$  per collision

# $K^0$ yield

$K^0_s \rightarrow \pi^+ \pi^-$  (69%)

CT = 2.68 cm

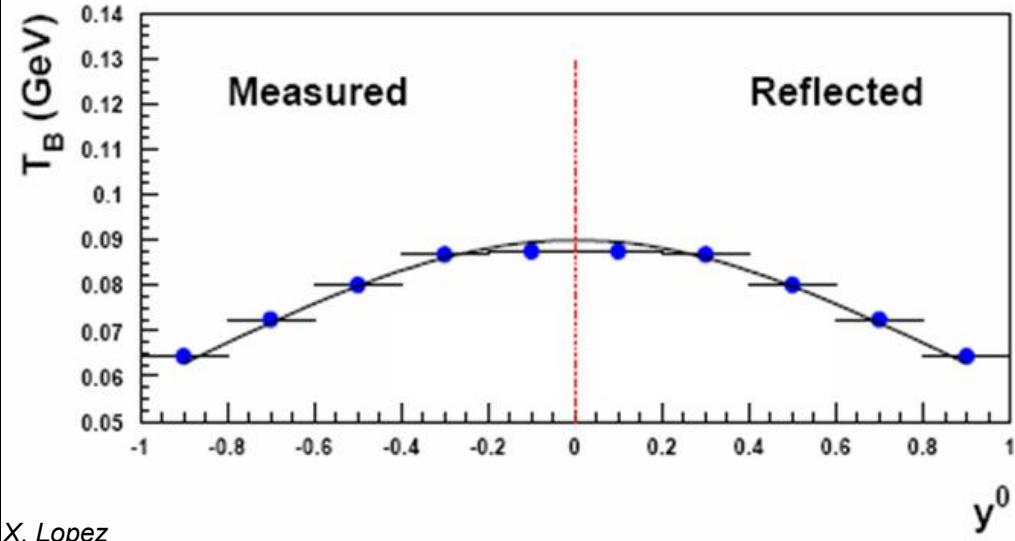
from secondary vertices



$\pi^+ \pi^-$  invariant mass spectrum

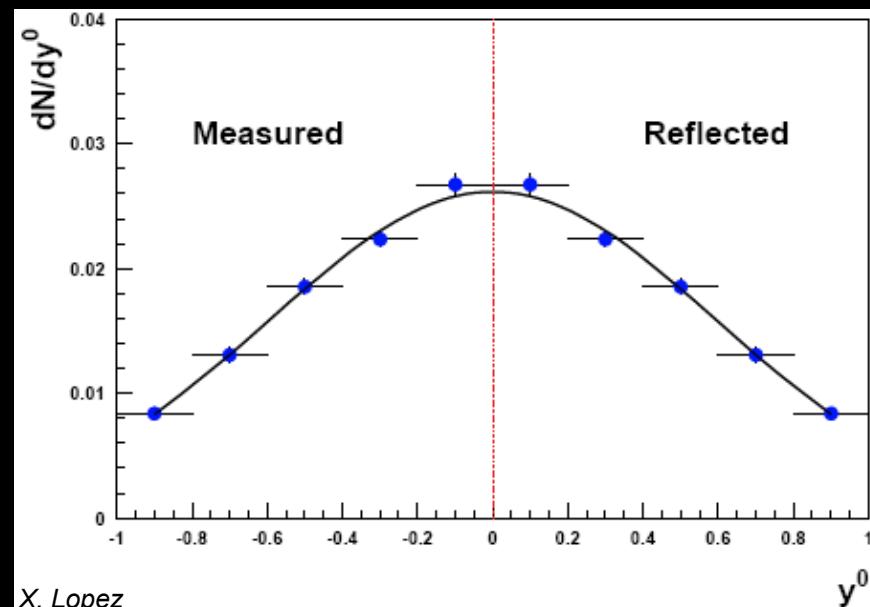
$M_t$  spectra

# $K^0$ yield



X. Lopez

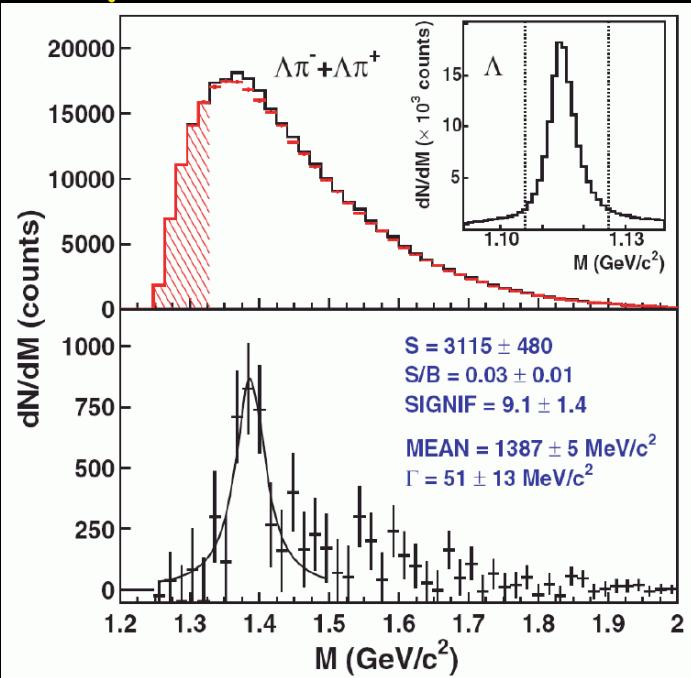
Total  $K^0$  yield:  
 $P(K^0) = 0.039 \pm 0.001 \pm 0.004$



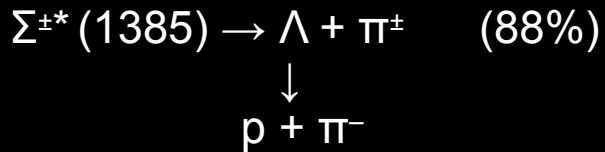
X. Lopez

The same procedure for  $\Lambda(1116)$  hyperons.

# $\Sigma^*, K^*$ resonances

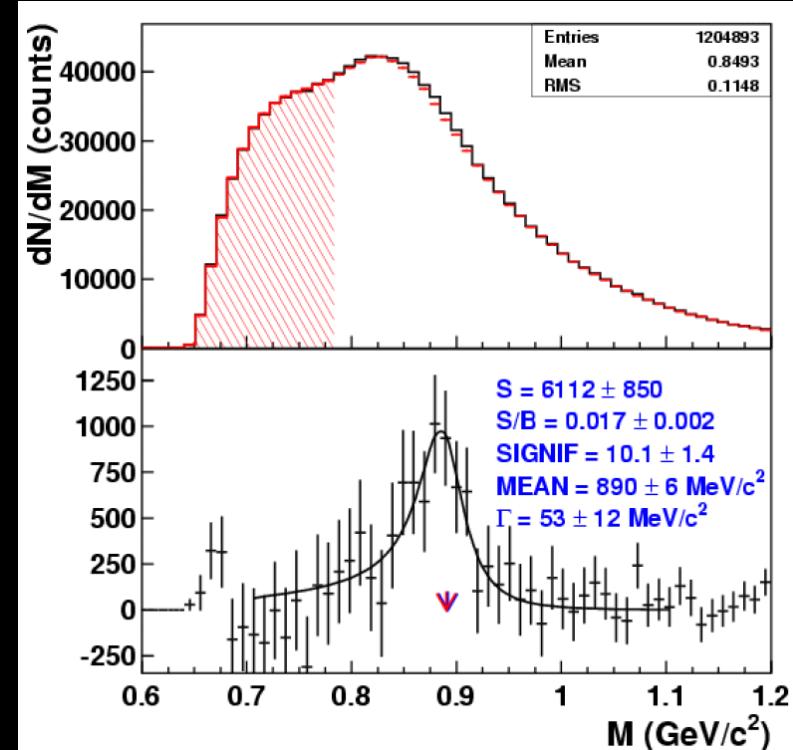


X. Lopez et al. (FOPI), PRC 76, 052203(R) (2007)

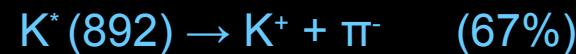


$E_{\text{th}} = 2.33 \text{ GeV}$   
 $\text{CT} = 5 \text{ fm}$

$$\frac{P(\Sigma^{*-} + \Sigma^{*+})}{P(\Lambda + \Sigma^0)} = 0.125 \pm 0.026 \pm 0.033$$



X. Lopez et al. (FOPI), J. Phys. G 35 (2008) 044020



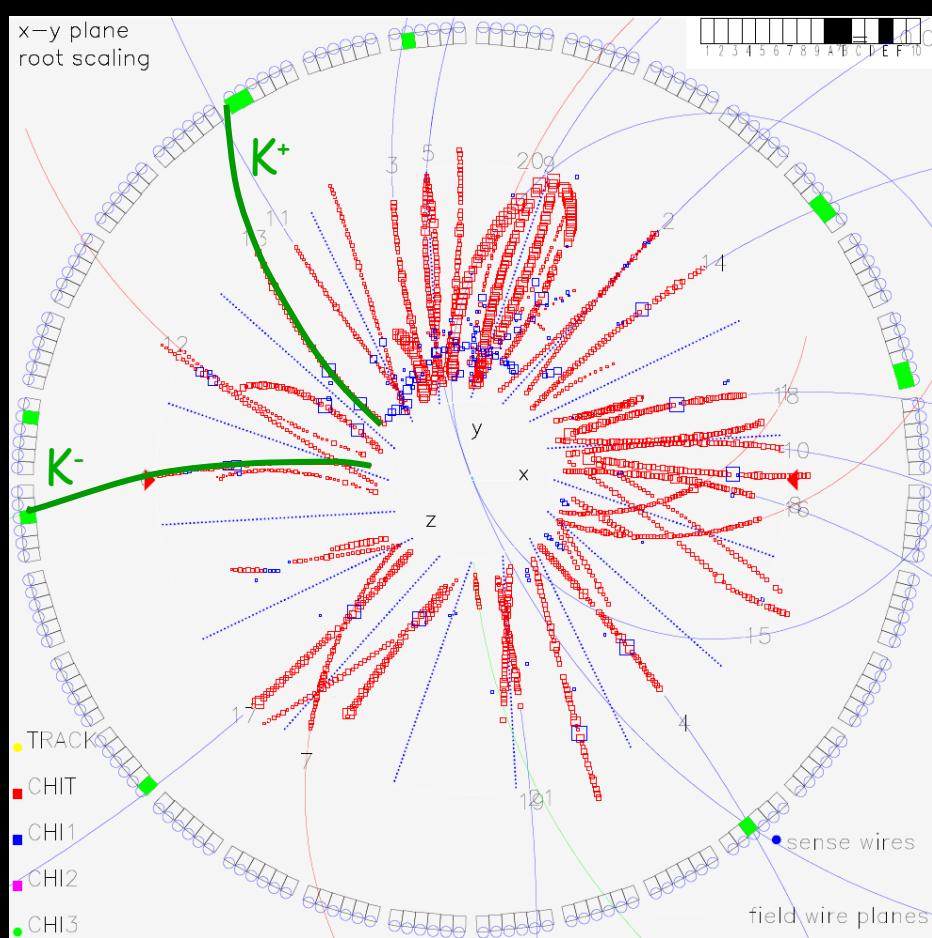
$E_{\text{th}} = 2.75 \text{ GeV}$   
 $\text{CT} = 4 \text{ fm}$

$$\frac{P(K^{0*})}{P(K^0)} = 0.032 \pm 0.003 \pm 0.012$$

# $\Phi(1020)$ production

$\phi(s\bar{s})$   
 $m_\phi = 1.019 \text{ GeV}/c^2$   
 $T \approx 1.55 \cdot 10^{-22} \text{ s}$   
 $E_{\text{thr}} = 2.6 \text{ GeV}$

(subthreshold production)

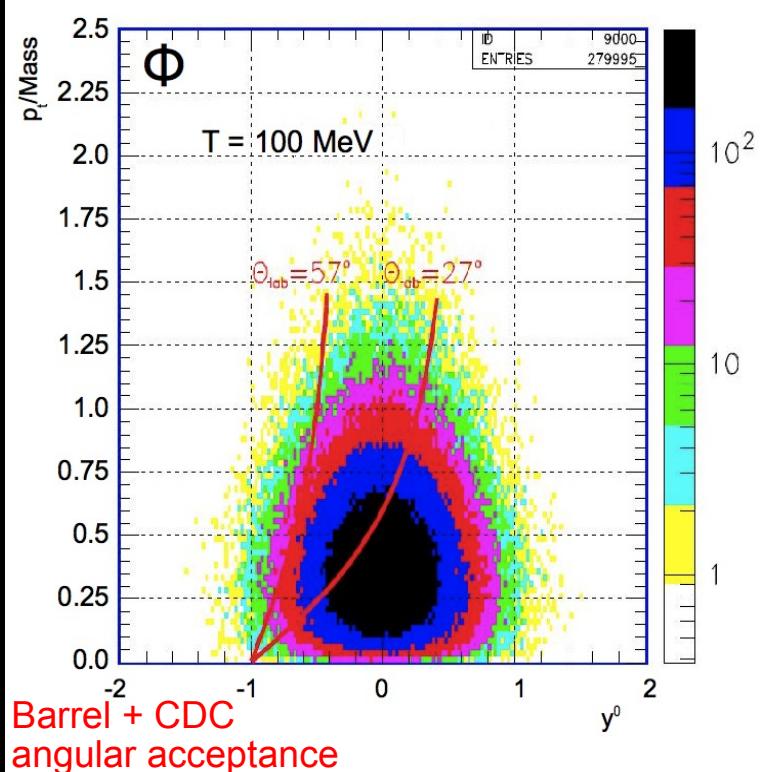
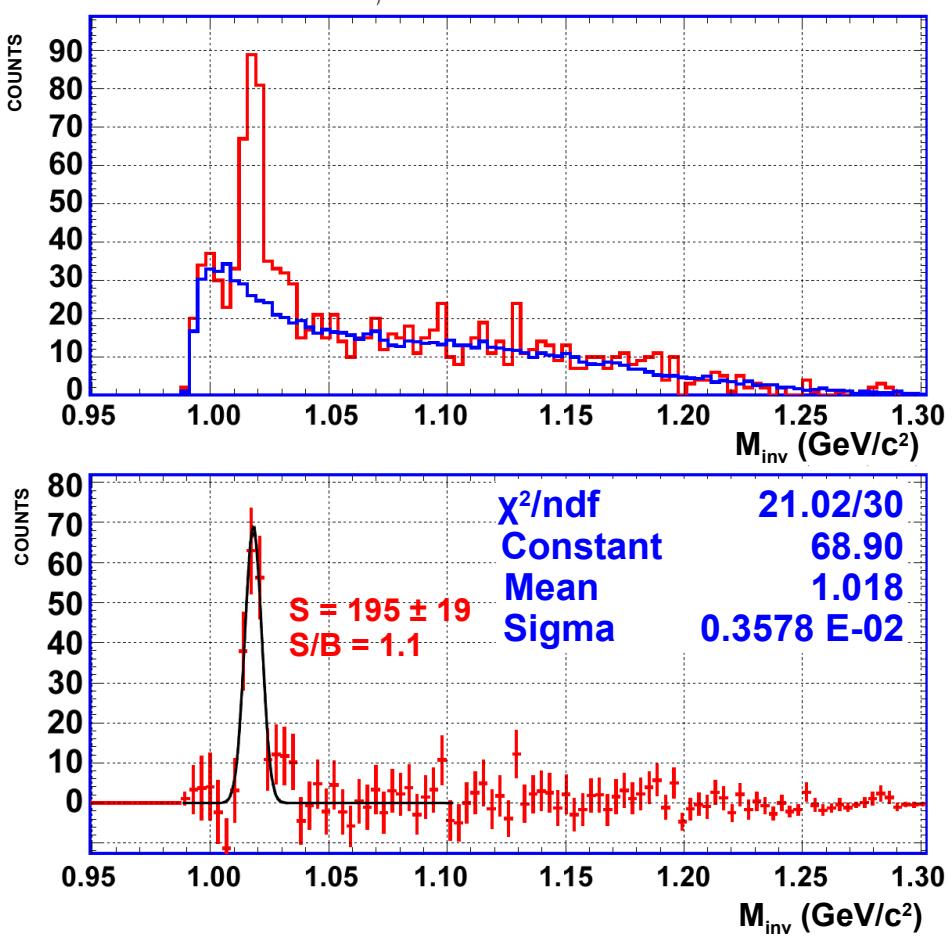


$cT \approx 50 \text{ fm} \rightarrow \phi$  decays in target  $\rightarrow$  no secondary vertex

$K^+K^-$  invariant mass reconstruction

B.R.  $_{\phi \rightarrow K^+K^-} = 49.2 \pm 0.6 \%$

# $\Phi$ reconstruction



- Invariant mass of  $K^+K^-$  pairs.
- Background reconstructed using „event-mixing” method

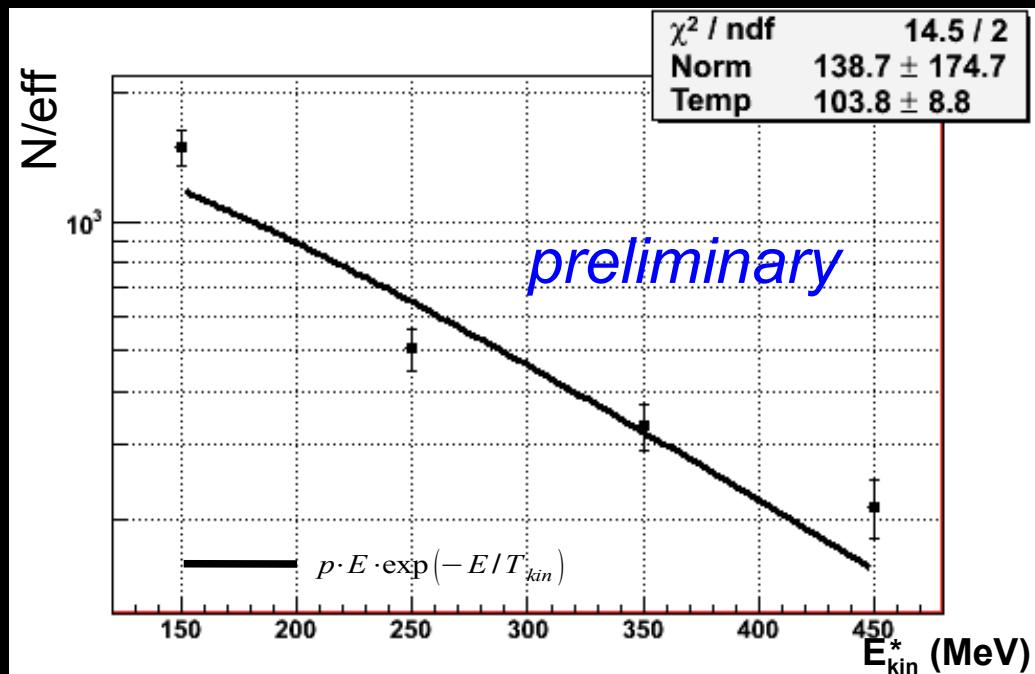
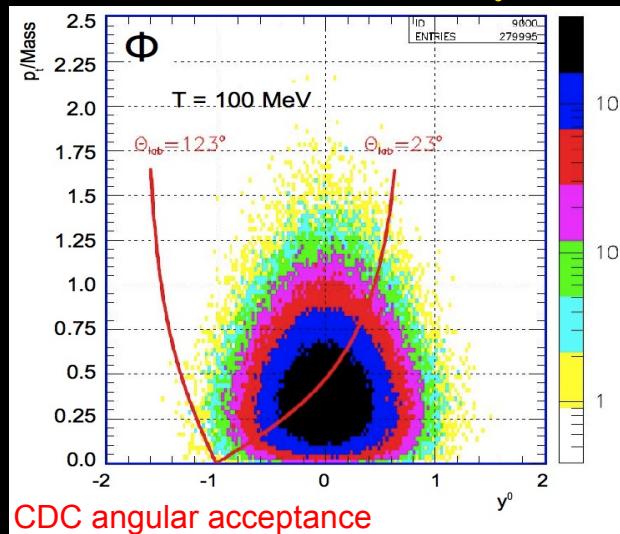
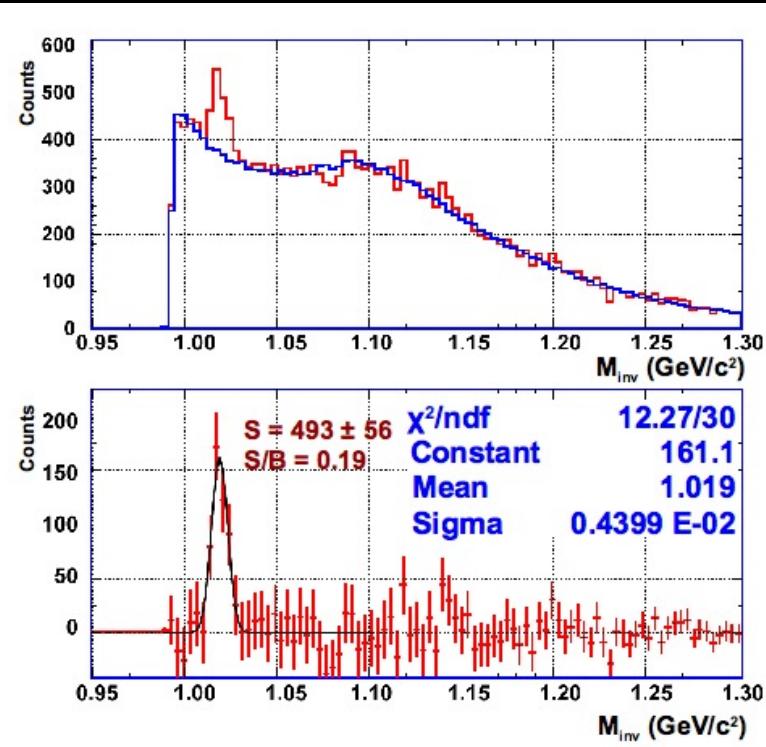
- FOPIs efficiency obtained with GEANT
- $\phi$ s generated from isotropic, thermal source (Siemens – Rasmussen formula)
- $T_{\text{source}} = 70 \dots 130 \text{ MeV}$  (errors estimation)
- $\beta_{\text{flow}} = 0$

Total yield in  $4\pi$ :  $P_\phi = (2.2 \pm 0.5) \cdot 10^{-4}$

# Extension of geometrical acceptance - $T_{\text{kin}}$

- Attempt to enlarge phase space of reconstructed  $\phi$  mesons
- CDC-only analysis
- Bigger statistics (signal  $\approx 500$ !)
- $T_{\text{kin}}$  estimation

$$T_{\text{kin}} = 104 \pm 9 \text{ MeV}$$

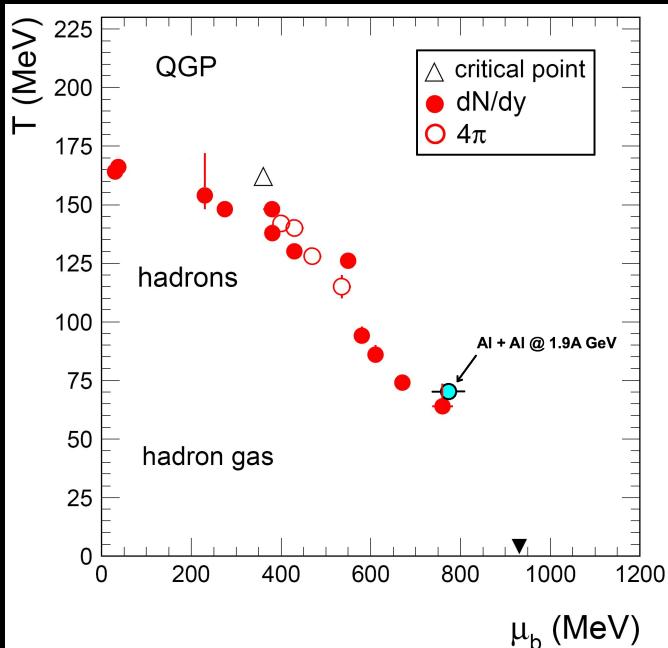


# Particle yields, Statistical Model - $T_{\text{chem}}$

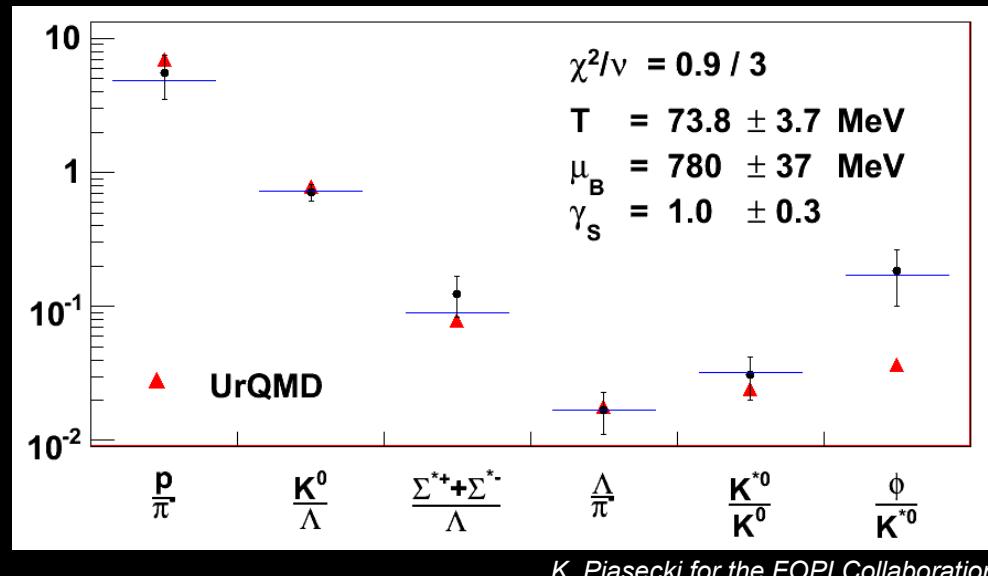
## Statistical Model:

*THERMUS code*  
*S. Wheaton, J. Cleymans*  
*hep-ph/0407175*

- Grand Canonical ensemble
- For strange particles, Canonical ensemble
- Model fitted to 6 independent ratios
- Parameters obtained:
  - $T_{\text{chem}} = 73.8 \pm 3.7 \text{ MeV}$
  - $\mu_B = 780 \pm 37 \text{ MeV}$
- Fairly good description by thermal model



A.Andronic,  
 P.Braun-Munzinger,  
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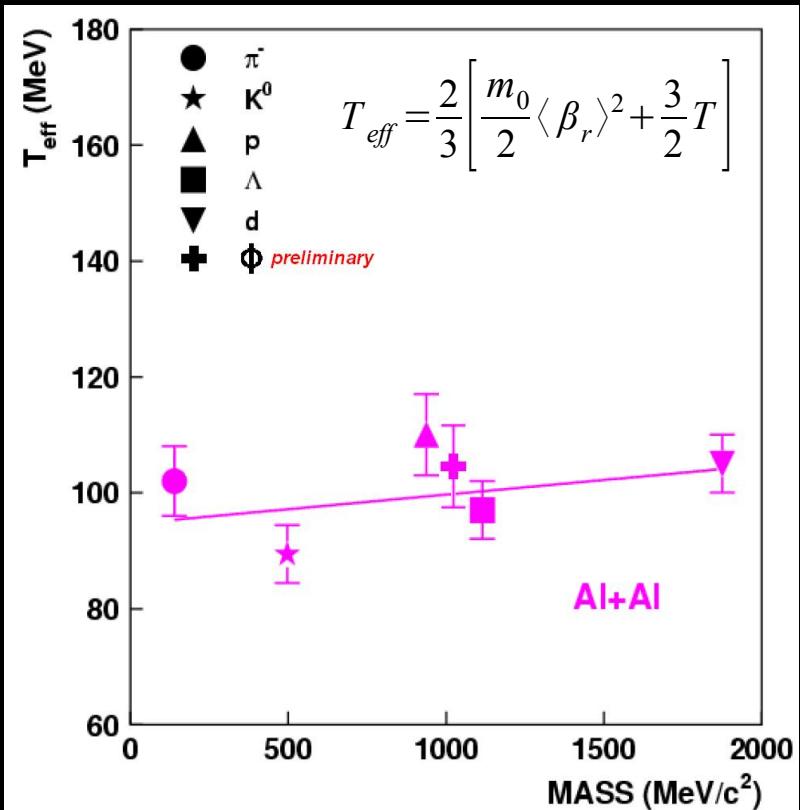


## UrQMD:

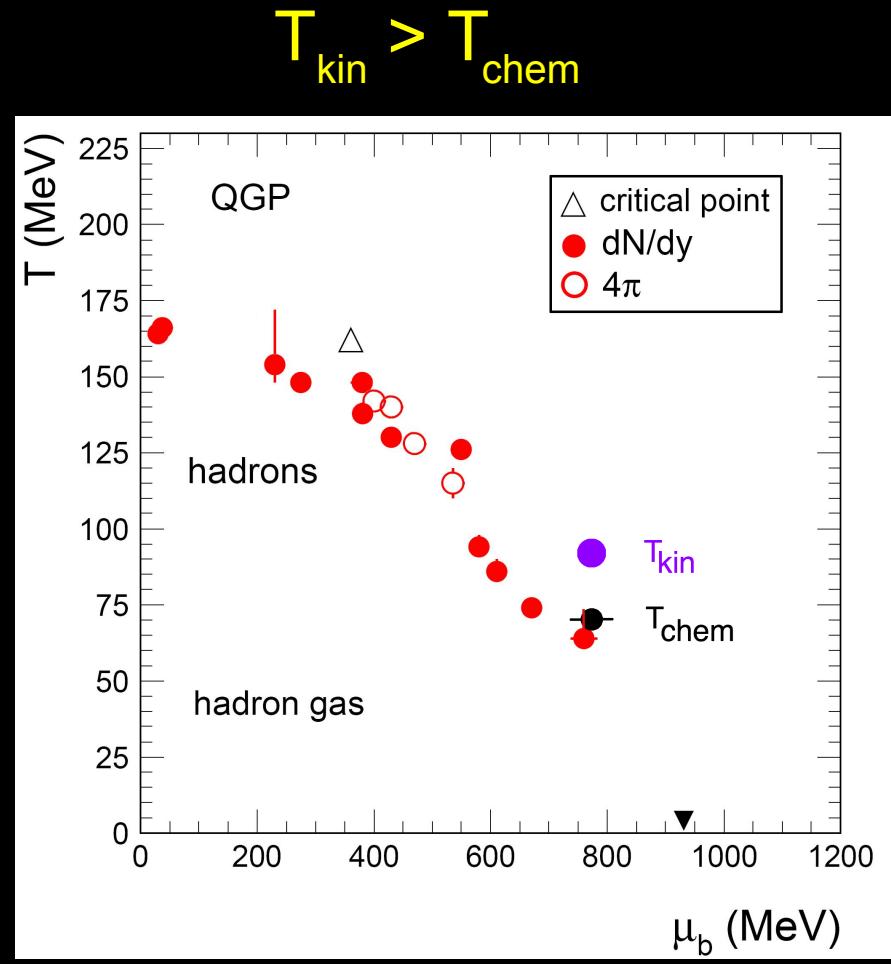
*M.Bleicher, S.Vogel*  
*Uni Frankfurt*

- No assumption for thermalisation
- No in-medium effects
- $\phi$  production mechanism poorly described

# Kinematical freeze-out



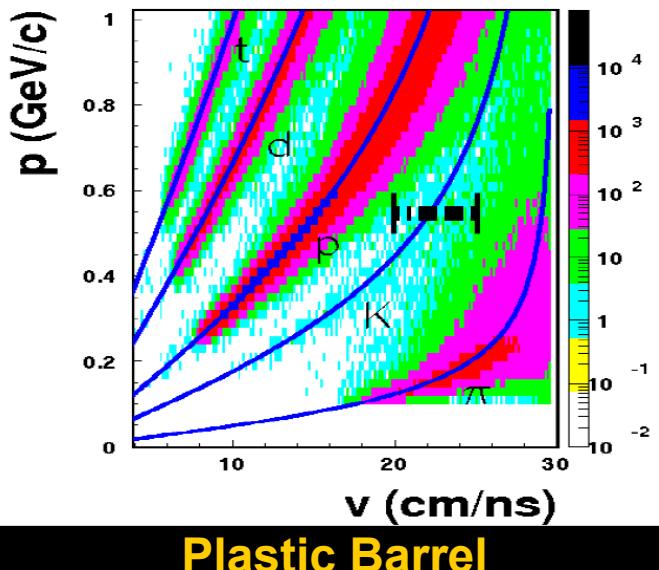
- $T_{kin} = 90 \dots 100 \text{ MeV}$
- $T_{chem} \approx 74 \text{ MeV}$



# Conclusions

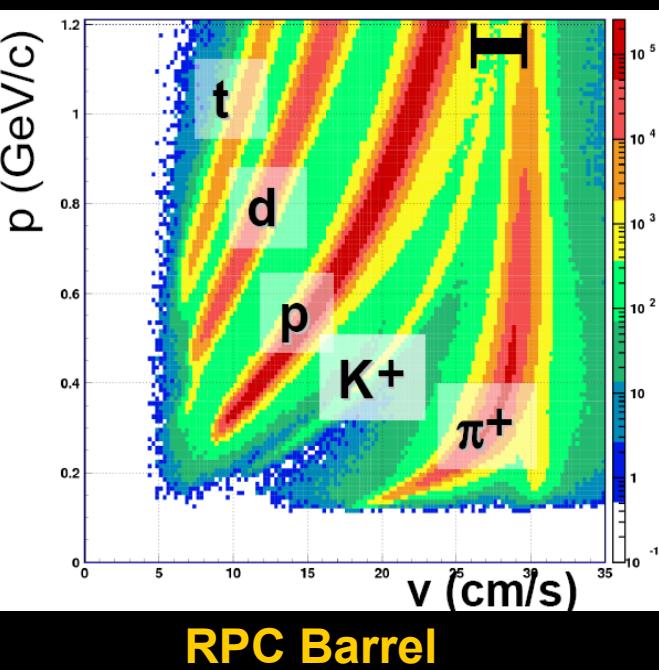
- Thermal model describes obtained ratios
- $T_{\text{chem}}$  in agreement with other experiments
- Temp. inversion:  $T_{\text{kin}} > T_{\text{chem}}$  (!!!)

What does it mean?



# Outlook

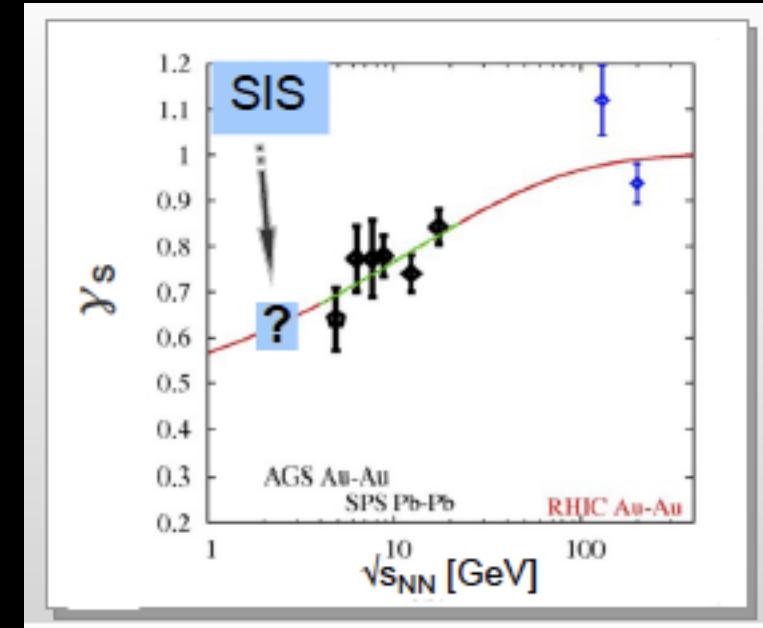
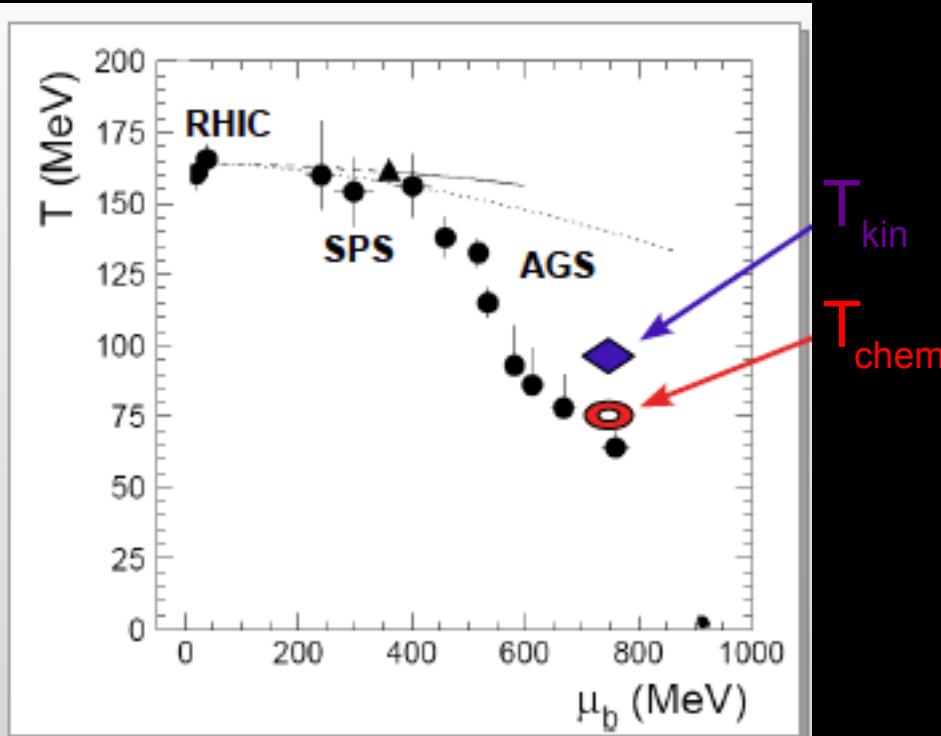
- Get as many particle ratios as possible
  - better statistics to obtain  $T_{\text{chem}}$  and  $T_{\text{kin}}$
- New ToF detectors in FOPI – RPC Barrel
  - larger ToF angular acceptance
  - high resolution:  $\sigma_{\text{ToF}} < 65 \text{ ps}$
- New data collected: Ni+Ni, Ru+Ru, Ni+Pb
  - analysis on going



# THANK YOU!

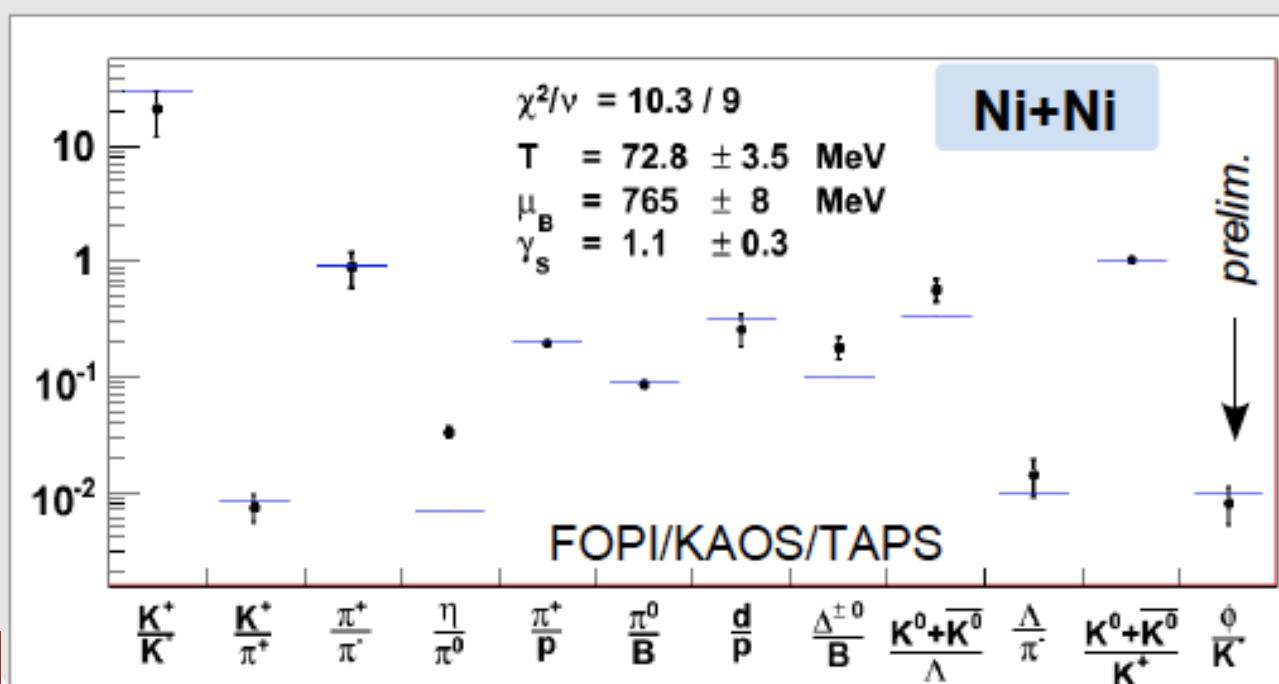
# Backup

J. Cleymans, et al., PRC 73, 034905 (2006)



F. Becattini et al., PRC 73, 044905 (2006)

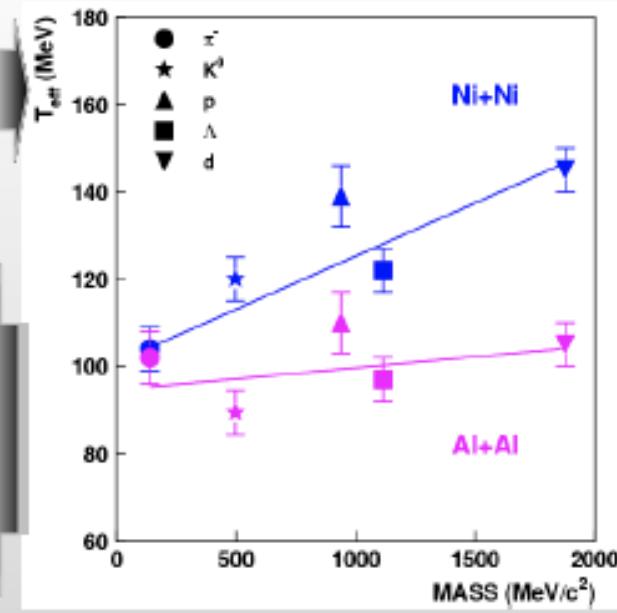
# Backup 2



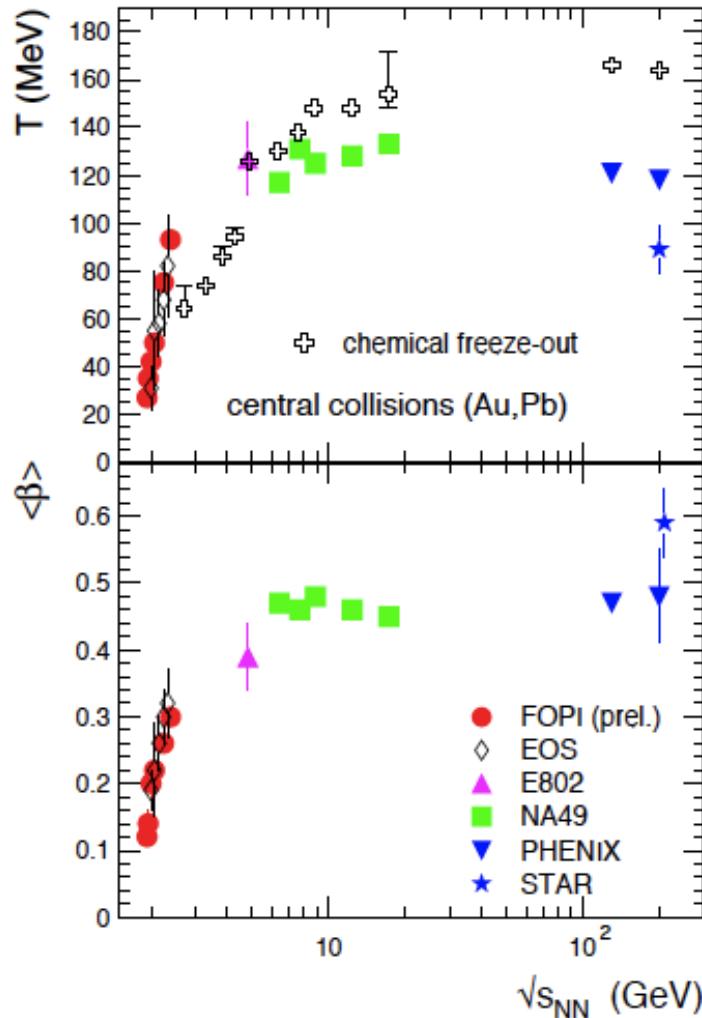
K. Piasecki for the FOPI Collaboration  
„Strangeness Production and Equilibration  
in Near-Threshold Heavy Ion Collisions in FOPI”  
PDG - 17.03.2009

$$T_{\text{eff}} = T + \frac{2}{3} \cdot \frac{m_0 \langle \beta_{\text{rad}} \rangle^2}{2}$$

- Ni+Ni: radial flow  
Al+Al: almost no expansion
- Same kinetical freeze-out T  
( $T \sim 90..100$  MeV)



# Backup 3



- AGS energies:  $T_{chem} < T_{kin}$  !
- bias in the thermal fits?

A. Andronic  
„Hadron production at chemical equilibrium“  
Nuclear Matter Physics at SIS100  
27.04.2009 - GSI/Darmstadt